Cygnus X-1: A Spinning Black Hole?

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Abstract. It has been a long-standing puzzle in black hole studies what triggers the spectral transition between the hard and soft states observed of Cygnus X-1, a prototypical black hole candidate. In this paper, we will make an attempt to address this issue in light of our recent work on black hole spin and its observational consequences.

1. Introduction

Cygnus X-1 is the first dynamically determined black hole (Webster & Murdin 1972; Bolton 1972). It is in a binary system with a massive O9.7 Iab supergiant, and the orbital period was determined optically to be 5.6 days. Cyg X-1 is thus intrinsically different from the majority of known black holes (BHs) whose companion stars are much less massive ($< M_\odot$). Curiously, *all* high-mass black hole binaries (BHBs), including Cyg X-1, LMC X-1 and LMC X-3, are persistent X-ray sources, while their low-mass counterparts are exclusively transients.

Since its discovery, Cyg X-1 has been considered as an archetypical stellar-mass black hole. Its observed spectral and temporal X–ray properties have, therefore, often been used to distinguish BHBs from their neutron star counterparts. Though seriously flawed, this approach has resulted in the discovery of many BHBs whose candidacy was later confirmed by dynamical mass measurement based on optical observations. Despite such success, little is known about the physics behind many observed phenomena for Cyg X–1, such as its transitions between the hard (≡ low) and soft (≡ high) states.

Cyg X-1 spends most of the time in the hard state where the soft X-ray (usually 2–10 keV) luminosity is low and the energy spectrum is hard. Occasionally (roughly once every 4 years on average), the soft flux suddenly jumps up by about a factor of 2 and the spectrum becomes much softer, i.e., the soft state. Such a state typically lasts only for several months before the source restores to the normal hard state. A complete episode of the hard-to-soft transition, soft state, and soft-to-hard transition occurred in 1996. It was discovered by the All-Sky Monitor (ASM) on RXTE (Cui 1996) and extensively monitored by

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both ASM and BATSE (Cui et al. 1996; Zhang et al. 1996a,b; also see Cui et al. 1997a,b,c,d, and Zhang et al. 1997a for detailed studies).

The observed X-ray emission is the result of gravitational energy release during mass accretion process. For Cyg X-1, the mass accretion is thought to be mediated by a so-called "focused wind" from the companion star that nearly fills its Roche-lobe (Gies & Bolton 1986), unlike transient BHBs where companion stars overfills the Roche-lobe. The observed orbital modulation at both X-ray and radio wavelengths (Zhang, Robinson, & Cui 1997; Fender, Brocksopp, & Pooley 1997) provides tentative evidence for such process, because it is thought to be caused by varying absorption optical depth through the stellar wind. This interpretation is based on the coincidence between the minimum of folded light curves and the superior junction (when the companion star is in front of the black hole). However, it is still not clear why X-ray modulation *only* seems to occur in the hard state, or at least it has so far not been observed for the soft state. In this paper, we make a critical assumption (but a very probable one) that Cyg X-1 is indeed a wind accretion binary.

2. Observations and Results

Figure 1 shows a long-term ASM light curve of Cyg X-1 that covers the entire 1996 episode. The soft state is indicated by a region between the two dashed-lines. Besides the rare occurrence of the soft state, the source also displays frequent brief flares in the hard state. The flaring activity appears to be quasi-periodic in nature with a period in the range 3–6 weeks. The duration of flares seems to vary from less than one day to tens of days. The most prominent flare occurred just prior to the hard-to-soft transition, and might actually be a characteristic precursor to such an event. Detailed studies of flaring phenomenon have not been possible, due to the lack of high-quality data, so its origin is still unknown. The situation is now much improved with the monitoring capability of two complementary all-sky monitors, ASM and BATSE. Combining data from both instruments, Zhang et al. (1997b) showed that the precursory flare seems to possess some of the spectral characteristics of the soft state, but the evidence is still tentative.

During the transition, the bolometric X-ray luminosity increases only mildly (less than a factor of 2; Zhang et al. 1997a), very different from transient BHBs where it typically varies by more than one order of magnitude during a transition. Therefore, a sudden increase of mass accretion rate, due to some instability, is unlikely responsible for triggering state transitions in Cyg X-1. Previously we (Zhang, Cui, & Chen 1997) noted that the observed X-ray spectrum of Cyg X-1 has a distinct ultra-soft component at low energies in both the hard and soft states. This spectral component is likely due to the emission from the innermost region of an optically thick, geometrically thin accretion disk. Unlike transient systems where the accretion process is probably through advection-dominated flows in the quiescent state (e.g., Narayan & Yi 1994), Cyg X-1 is a persistently luminous BHB. In this system, the disk is likely to extend to the last stable orbit, which is determined by the mass and spin of the black hole. Given the BH mass of 10-20 $M_{\odot}$ for Cyg X-1 from the optical radial velocity measurements (e.g., Gies & Bolton 1986; Herrero et al. 1995), the BH spin can

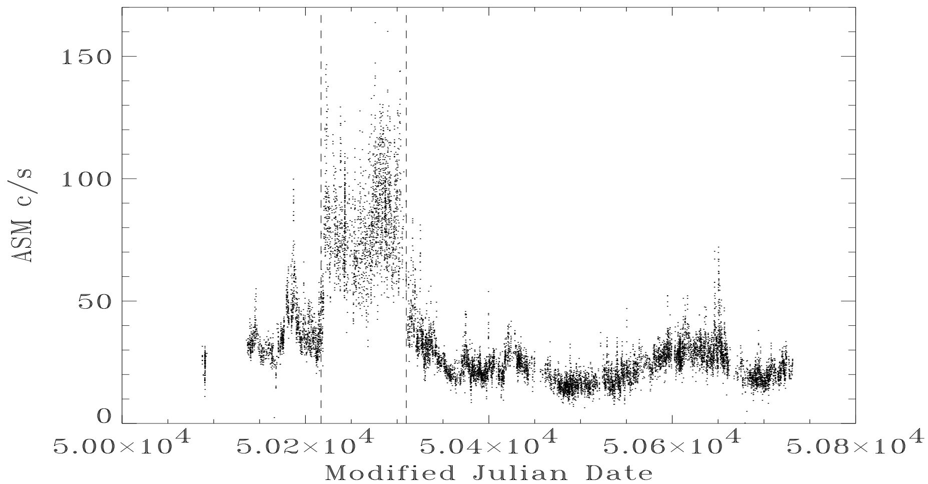

Figure 1. The long-term ASM light curve of Cyg X-1. The region between two dashed-lines indicates the period of soft state. Each data point represents a measurement with an integration time of 90 seconds. The energy band covered is between 1.3 and 12 keV.

therefore be derived by measuring the location of the inner disk edge. This was achieved by carefully characterizing the ultra-soft component (Zhang, Cui, & Chen 1997). This component can be modeled by a multicolor blackbody with the color temperature at the inner disk edge only $\sim$0.18 keV, much lower than typical values for transient BHBs, and a luminosity 5×10^{36} erg/s in the hard state. Approaching the soft state, the color temperature increases by a factor of $\sim$2.4, and the flux by a factor of $\sim$3. Together they imply a decrease of the inner disk radius by a factor of $\sim$3.4, which is *quantitatively* consistent with a simple reversal of the accretion disk, from retrograde to prograde, if the central black hole spins at about 75% of the maximal rate (see Zhang, Cui, & Chen 1997 for more details). The disk reversal in Cyg X-1 is actually a revitalized idea, originally proposed by Shapiro and Lightman (1976).

3. Discussion

One obvious question is whether disk reversal can actually occur in a real binary system. For most BHBs where mass accretion is due to Roche-lobe overflow of the companion star, the angular momentum of accreting matter is almost entirely determined by binary orbital motion, thus seems nearly impossible to imagine a reversal of the accretion flow. For wind accretion systems like Cyg X-1, however, the fluctuation in residual angular momentum of the flow behind the hole can cause flip-flop of the disk. This phenomenon has been demonstrated by both 2D (Matsuda, Inoue, & Sawada 1987; Benensohn, Lamb, & Taam 1997) and 3D (Ruffert 1994a,b, 1995, 1996, 1997) numerical simulations, although the effects are much suppressed in 3D cases. Moreover, Benensohn et al. (1997)

showed that the disk flip-flop occurs quasi-periodically on binary dynamical time scales. *Could this be the origin of brief flares observed in the hard state for Cyg X-1?* Perhaps, the soft state is simply a strong, prolonged flare which only occurs on rare occasions. If so, similar spectral evolution would be expected during a flare, just like during a state transition. A definitive answer will await detailed, systematic studies of the flaring activity in Cyg X-1. Unfortunately, the flares are usually very brief, thus are difficult to catch. A monitoring program with RXTE seems to be the only way in near future to obtain essential data for such investigations.

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